SOLID-STATE GYROSCOPES AND PLANAR THREE-AXIS INERTIAL MEASUREMENT UNIT

BACKGROUND OF THE INVENTION

1. Field of the Invention

[0001] The present invention relates to solid-state gyroscopes and a three-axis inertial measurement unit, which are in particular manufactured by a micro-mechanical technique, and can sense three axes angular velocities and three axes accelerations simultaneously.

2. The Related Art

[0002] The sensing axis of angular velocity for most of conventional gyroscopes manufactured by a micro-mechanical technique is parallel to the structure surface thereof. Furthermore, in case of needing to concurrently sense three axial angular velocities and accelerations, if the sensing axis of angular velocity is perpendicular to the structure surface thereof, the gyroscopes and accelerometers can be built on a single chip to measure three axial angular velocities and accelerations, and the cost and size thereof can be thus largely reduced. Therefore the other types of gyroscopes are born.

SUMMARY OF THE INVENTION

[0003] Figure 1 shows a configuration of a conventional solid-state gyroscope, comprising two proof masses 3 and two comb drivers 31, 32 corresponding to each proof mass. Its sensing axis is perpendicular to the structure surface thereof. The proof masses 3 and the comb drivers 31, 32 are connected to an anchor 60 fixed on a substrate 71 by a number of elastic beams 6, 61, 62. The proof masses 3 have a number of regularly arranged holes 3h. The surface of the substrate 71 there under includes a number of pairs of stripe electrodes 91, 92 perpendicular to a sensing axis (x-axis) and respectively connected to bond pads 9p, 9n. The distance between corresponding points of the holes 3h along the x-axis is the same as that of the pairs of stripe electrodes 91, 92. The pairs of stripe electrodes 91, 92 and the surface of the proof mass 3 are formed two sensing capacitors c9p, c9n. The proof masses 3, comb drivers 31, 32 and elastic beams 6, 61, 62 may be formed from metal, doped silicon, silicon, or poly-silicon. The lengths, widths and thickness of the elastic beams 6, 61,

62 are designed to facilitate the two axial compliances parallel to the structure surface thereof.

[0004] The two outer comb drivers 31 are respectively excited with a DC bias and an AC voltage at the mechanical resonant frequency thereof to cause the two proof masses 3 to vibrate in the opposite direction along the y-axis. The two inner comb drivers 32 are respectively excited with a DC bias and a high frequency AC voltage of opposite phase, and are mainly used to sense the driven amplitudes of the proof masses 3 and feedback the signals thereof for controlling the driven amplitudes. If a z-axial angular velocity input, a Coriolis force makes the two proof masses 3 vibrate in the opposite direction along the x-axis and causes a change in the capacitances of the sensing capacitors c9p, c9n. The sensing capacitors c9p, c9n are respectively excited with a DC bias and a high frequency AC voltage of opposite phase. The current sensed from the output node GN is proportional to the differential displacement of the two proof masses 3.

[0005] There is another type of sensing capacitor, a comb capacitor (not shown in Figure 1), being able to be used to sense the movements of the proof masses 3 along the x-axis. When the proof masses 3 move along the x-axis, the change in the distance of the capacitors results in the change in the capacitance thereof, which can be used to sense the displacements of the proof masses 3.

[0006] Although the second type of the conventional solid-state gyroscope can sense the angular velocity perpendicular to the structure surface thereof, it is more difficult to manufacture a practical electrostatic comb driver or a comb sensing capacitor. The reason is that they have two deep and spaced narrow vertical surfaces, which are suitable for being manufactured by dissolved wafer process, surface micromachining, and dry etching. The aspect ratio decreases with the increase in depth. The sensitivity thereof is also limited. The bulk micromachining techniques with larger structures are not suitable here.

[0007] The improvements of the present invention comprise: the drivers and the sensors using a structure of stripe capacitors with an edge effect; the manufacturing process being simple; no need to manufacture two deep and spaced narrow vertical surfaces; no special manufacturing process requirement of high aspect ratio; and suitable for multiple fabrication techniques.

[0008] In summary, the present invention discloses: (1) a z-axial solid-state gyroscope being able to sense an angular velocity perpendicular to the structure surface thereof and to sense an axial acceleration parallel to the structure surface thereof; (2) a solid-state gyroscope being able to sense an angular velocity parallel to the structure surface and to sense an axial acceleration perpendicular to the structure surface thereof; (3) two z-axial solid-state gyroscopes and two solid-state gyroscopes with sensing axes parallel to the structure surface thereof being designed on a single chip to form a functionally complete planar inertial measurement unit that can be concurrently manufactured in one manufacturing process, and the size and the manufacturing and assembling cost thereof can be largely reduced.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] The objects, effectiveness and configurations of the present invention will be more definitely understood after reading the detailed description of the preferred embodiment thereof with reference to the accompanying drawings.

[0010] Figure 1 is a schematic view of a configuration of a conventional solid-state gyroscope, which can sense an angular velocity perpendicular to the structure surface thereof.

[0011] Figure 2 is a schematic view of a configuration of a z-axial solid-state gyroscope in accordance with a preferred embodiment of the present invention, in which Figure 2a shows a top view of the main configuration thereof and Figure 2b shows a schematic view of stripe electrodes of driving capacitors and sensing capacitors on a surface of a glass plate.

[0012] Figure 3 is a cross-sectional schematic view of a configuration of the stripe electrodes of the driving capacitor and the sensing capacitor.

[0013] Figures 4 and 5 are schematic views of the configurations of the z-axial solid-state gyroscopes in accordance with another two preferred embodiments of the present invention.

[0014] Figure 6 is a schematic view of a configuration of a z-axial solid-state gyroscope, which is manufactured with a (110) silicon chip by bulk micromachining technique, in accordance with a preferred embodiment of the present invention, in which Figure 6a shows a top view of the main configuration thereof and Figure 6b

shows a schematic view of stripe electrodes of driving capacitors and sensing capacitors on a surface of a glass plate.

[0015] Figure 7 is a schematic view of a configuration of an x-axial solid-state gyroscope, the sensing axis thereof parallel to the structure surface thereof, in accordance with a preferred embodiment of the present invention, in which Figure 7a shows a top view of the main configuration thereof and Figure 7b shows a schematic view of stripe electrodes of driving capacitors and sensing capacitors on a surface of a glass plate.

[0016] Figure 8 is a schematic view of a configuration of a planar three-axis inertial measurement unit constructed by four solid-state gyroscopes, in which Figure 8a shows a configuration of a rectangular contour or a square contour thereof and Figure 8b shows a configuration of a parallelogram contour, manufactured with a (110) silicon chip by bulk micromachining technique.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

[0017] Referring to Figure 2a, which shows a schematic view of a configuration of a z-axial solid-state gyroscope of a preferred embodiment in accordance with the present invention, the configuration is manufactured with a conductive material and comprises an outer frame 2 and a central anchor 60. The interior of the outer frame 2 has two sets of a proof mass 3 and two driver bodies 51, 52. Each proof mass 3 is respectively connected to the corresponding two driver bodies 51, 52 thereof by at least one sensing elastic beam 4. Two connection beams 5 connect the two driver bodies 51, 52 to each other. Each proof mass 3 and the corresponding driver bodies 51, 52 thereof are respectively connected to a common connection beams 61 by a number of driving elastic beams 6. The common connection beams 61 are connected to a common elastic beams 62 fixed at the central anchor 60. Each proof mass 3 and the corresponding driver bodies 51, 52 thereof are also additionally suspended to the outer frame 2 by a number of elastic beams 65, 66.

[0018] Two glass plates 71, 72 are respectively positioned in front and rear of the main configuration thereof and mounted with the outer frame 2 and the anchor 60 together, so that the other elements are suspended between the two glass plates 71, 72. The sensing beams 4 make the proof masses 3 facilitate move along a specially designated direction (defined as x-axis) parallel to the surfaces of the glass plates 71,

72. The driving elastic beams 6, the common elastic beams 62, and the elastic beams 65, 66 make the proof masses 3 and the driver bodies 51, 52 facilitate move along another specially designated direction (defined as y-axis) parallel to the surfaces of the glass plates 71, 72. Both surfaces of the proof masses 3 respectively have a number of grooves 3t perpendicular to the x-axis. Both surfaces of the driver bodies 51, 52 respectively have a number of grooves 5t perpendicular to the y-axis.

[0019] The surface of each glass plate facing the silicon chip and corresponding to each driver body 51 includes two sets of interposed stripe electrodes 81, 82 parallel to the grooves 5t, which are respectively connected to a bond pads 81p, 81n (see Figure 2b). The relative positions of the grooves 5t on the surface of the driver bodies 51 and the corresponding stripe electrodes 81, 82 thereof are shown in Figure 3. Each surface of each driver body 51 and the corresponding stripe electrodes 81, 82 thereof respectively are formed two sets of driving capacitors c81p, c81n. In similar, the surface of each glass plate facing the silicon chip and corresponding to each driver body 52 include another two sets of interposed stripe electrodes 81, 82 parallel to the grooves 5t, which are respectively connected to a bond pads 82p, 82n. Another two sets of driving capacitors c82p, c82n are formed.

[0020] The surface of each glass plate facing the silicon chip and corresponding to the grooves 3t on the surface of each proof mass 3 thereof also include two sets of interposed stripe electrodes 91, 92 parallel to the grooves 3t, which are respectively connected to a bond pads 9p, 9n. Each surface of each proof mass 3 and the corresponding stripe electrodes 91, 92 thereof are formed two sets of sensing capacitors c9p, c9n.

[0021] The outer driving capacitors c81p, c81n are respectively excited with a DC bias and an AC voltage of opposite phase at the mechanical resonant frequency thereof to cause the two proof masses 3 to vibrate in the opposite direction along the y-axis. The inner driving capacitors c82p, c82n are respectively excited with a DC bias and an high frequency AC voltage of opposite phase thereof, and are mainly used to sense the driven amplitude of the proof masses 3 and feedback the signal thereof for controlling the driven amplitude.

[0022] If a z-axial angular velocity input, a Coriolis force makes the two proof masses 3 vibrate in the opposite direction along the x-axis. If an x-axial acceleration

input, a specific force makes the two proof masses 3 move in same direction along the x-axis. Both inertial forces make the areas of the stripe capacitors change and thus make the capacitances of the sensing capacitors c9p, c9n change.

[0023] The sensing capacitors c9p, c9n are respectively excited with a DC bias and a high frequency AC voltage of opposite phase. The current sensed from the output node GN is proportional to the differential displacement of the two proof masses 3. The signals induced by an angular velocity and acceleration is respectively an AC signal and a low frequency or DC signal, which can be separated into a z-axial angular velocity and an x-axial acceleration signal by a signal processing technique. A part of the stripe electrodes 91, 92 of the sensing capacitors c9p, c9n can be isolated as a feedback electrode 9f (see Figure 2b) for the rebalancing of the Coriolis force.

[0024] There are many different types of the structure shown in Figures 4 and 5. The grooves 3t, 5t on the surfaces of the proof masses 3 and the driver bodies 51, 52 are further etched a plurality of deep holes or through holes 3h, 5h to lessen the burden of the drivers and thus promote the driving performance thereof. In addition, as shown in Figure 4, the connection beams 5 are deleted but the sensing beams 4 still connect to the two driver bodies 51, 52. Referring to Figure 5, the sensing beams 4 and the connection beams 5 are deleted, the proof masses 3 and the two driver bodies 51, 52 are directly connected together, the roles of the sensing beams 4 are instead of the common connection beams 61.

[0025] The configuration of the present invention can be manufactured by dissolved wafer process, surface micromachining, dry etching, LIGA, and bulk micromachining etc. There has no need to fabricate two deep and spaced narrow vertical surfaces same as those of a conventional comb structure, i.e., no special manufacturing process requirement of high aspect ratio.

[0026] As shown in Figure 6, the configuration of the present invention is manufactured with a (110) silicon chip by bulk micromachining technique. Due to the non-isotropic wet etching characteristic, the shapes of the device and most elements thereof are parallelogram, the included angle of any two sides being 109.48° or 70.52°. Except shapes, all of the elements and the functions thereof are the same as those of Figure 4. The (110) silicon chip has the advantages of perpendicularly deep-etching and automatically stop-etching, so the fabrications of the driving beams 6 and

the sensing beams 4 are more simple. The widths of the driving beams 6 and the sensing beams 4 and thus the driving and the sensing resonant frequencies thereof can be precisely controlled. Therefore the yield rate of and the sensing performance thereof can be promoted. Because the driving beams 6 and the sensing beams 4 are not orthogonal but 109.48° or 70.52°, the effective Coriolis force is reduced to sin(109.48°) or sin(70.52°) times of its original value, that is 0.94 times. That means the sensitivity being reduced to 0.94 times of its original value.

[0027] A new coordinate system (x', y', z) is defined by rotating an original coordinate system (x, y, z) an angle θ, 19.48°, about z-axis. If the driving beams 6 are parallel to the x-axis, the sensing beams 4 are parallel to the y'-axis. Therefore the driving direction is in the y-axis and the sensing capacitors c9p, c9n can sense a z-axial angular velocity Wz and an x'-axial acceleration Ax'.

[0028] The above two z-axial solid-state gyroscopes and two in-plane axial gyroscopes can be designed on a single chip to form a functionally complete planar inertial measurement unit having functions of three-axial gyroscopes and three-axial accelerometers.

[0029] Figure 7 shows a schematic view of an x-axial solid-state gyroscope in accordance with the present invention, the sensing axis thereof being parallel to its structure surface. Figure 7a is a top view of the configuration thereof. Figure 7b shows a schematic view of interposed stripe electrodes 81, 82 of the driving capacitors and electrodes 9 of the sensing capacitors on the surface of a glass plate 71. The configuration of the x-axial solid-state gyroscope in Figure 7 is substantially same as that of the z-axial solid-state gyroscope in Figure 2. The major differences between both gyroscopes are: (1) the sensing beams 4 of the x-axial solid-state gyroscope making the proof masses 3 facilitate move along the z-axis, but along the x-axis for the z-axial solid-state gyroscope in Figure 2; and (2) each sensing electrode on each glass plate corresponding to each proof mass 3 for the x-axial solid-state gyroscope being a single electrode 9, but two sets of interposed stripe electrodes 91, 92 for the z-axial solid-state gyroscope.

[0030] To assemble a planar three-axis inertial measurement unit, a y-axis solid-state gyroscope is required except the above x-axial and z-axial gyroscopes, which

configuration is the same as the x-axial solid-state gyroscope but rotates an angle about the z-axis.

[0031] Four solid-state gyroscopes are assembled to form a planar three-axis inertial measurement unit. The axial arrangements of the driving axis, the sensing axis, the angular velocity input axis, and the acceleration input axis for various gyroscopes are summarized in Table 1 in case of the square or rectangular structure.

Table 1: The axial arrangements for various gyroscopes in case of the square or the rectangular structure.

Gyroscope No.	Driving axis	Sensing axis	Angular velocity input axis	Acceleration input axis
G1	Dy	Dz	Wx	Az
G2	Dx	Dz	Wy	Az
G3	Dy	Dx	Wz	Ax
G4	Dx	Dy	Wz	Ay

[0032] From Table 1, there are two sets of output signals of z-axial angular velocity and acceleration.

[0033] If a planar three-axis inertial measurement unit is assembled with a z-axial solid-state gyroscope and two in-plane axial solid-state gyroscopes, there are two sets of z-component acceleration signals, Az, but lack of a set of acceleration signal in in-plane axial component. For example if gyroscope G4 is deleted, there is lack of a y-component acceleration, Ay. If gyroscope G3 is deleted, there is lack of an x-component acceleration, Ax. To supplement the signal of the x-component or y-component acceleration, an x-axial or y-axial accelerometer needs to be added.

[0034] If a planar three-axis inertial measurement unit is manufactured with a (110) silicon chip by bulk micromachining technique, the axial arrangements of the driving axis, the sensing axis, the angular velocity input axis, and the acceleration input axis for various gyroscopes are summarized in Table 2.

Table 2 The axial arrangements for various gyroscopes in case of the parallelogram structure.

Gyroscope No.	Driving axis	Sensing axis	Angular velocity input axis	Acceleration input axis
G1	Dy	Dz	Wx	Az
G2	Dx'	Dz	Wy'	Az
G3	Dy	Dx'	Wz	Ax'
G4	Dx'	Dy	Wz	Ay

[0035] Figure 8a shows a schematic view of a planar three-axis inertial measurement unit constructed by four solid-state gyroscopes in accordance with the present invention, wherein the axial arrangements of the driving axis, the sensing axis, the angular velocity input axis and the acceleration input axis for various gyroscopes is the same as that listed in Table 1.

[0036] Figure 8b shows a schematic view of a planar three-axis inertial measurement unit constructed by four solid-state gyroscopes, being manufactured with a (110) silicon chip by bulk micromachining technique, in accordance with the present invention, wherein the axial arrangements of the driving axis, the sensing axis, the angular velocity input axis and the acceleration input axis for various gyroscopes is the same as that listed in Table 2.

[0037] For a planar three-axis inertial measurement unit manufactured with a (110) silicon chip by bulk micromachining technique, the finally obtained signals include three angular velocity components Wx, Wy', Wz and three acceleration components Ax', Ay, Az. Due to the x-axis and the y'-axis, and the x'-axis and the y-axis being non-orthogonal, (Wx, Wy') and (Ax', Ay) need to be transferred to an orthogonal coordinate system (x, y, z) or (x', y', z'). From the relationship of the coordinate systems (x, y, z) and (x', y', z') shown in Figure 6b, the transformation formula thereof are the following:

$$W_y=(-W_x \sin\theta + W_{y'})/\cos\theta,$$

$$A_x=(A_{x'} + A_y \sin\theta)/\cos\theta.$$

[0038] The output signals of the above planar three-axis inertial measurement unit of the present invention include three axial angular velocity components and three axial acceleration components. If less component signals are needed, the configurations thereof can be suitably simplified.

[0039] The above description is only for illustrating the preferred embodiments of the present invention, and not for giving any limitation to the scope of the present invention. It will be apparent to those skilled in this art that all equivalent modifications and changes shall fall within the scope of the appended claims and are intended to form part of this invention.